COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF INTERNAL AFFAIRS

HISTORY, PRESENT STATUS and FUTURE POSSIBILITIES of SECONDARY RECOVERY OPERATIONS in PENNSYLVANIA

[Oil]

By

William S. Lytle

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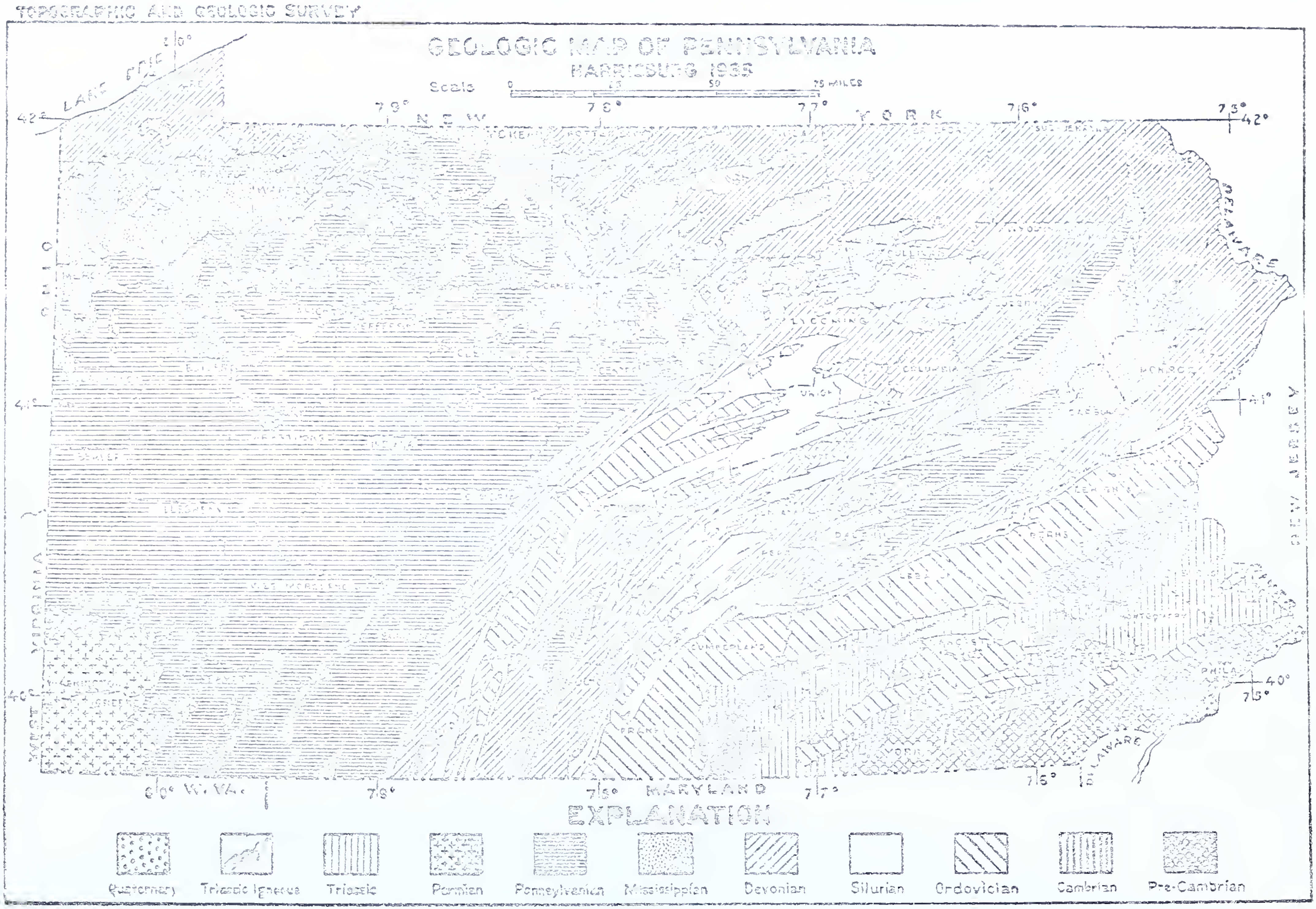
TOPOGRAPHIC AND GEOLOGIC SURVEY
GEOLOGIC MAP OF PENNSYLVANIA
HARRISBURG 1935
Scale
0
50
75 MILES
LAKE ERIE
NEW YORK
OHIO
WEST VIRGINIA
W. VA.
MARYLAND
NEW JERSEY
DELAWARE
LYCOMING
COLUMBIA
MONROE
CUMBERLAND
YORK
PHILA.
EXPLANATION
Quaternary
Triassic Igneous
Triassic
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Pre-Cambrian

Figure 1

HISTORY, PRESENT STATUS, and FUTURE POSSIBILITIES OF SECONDARY RECOVERY OPERATIONS IN PENNSYLVANIA

By

William S. Lytle*

INTRODUCTION

Pennsylvania is proud of its many firsts in the history of crude oil production. This year's Petroleum Centennial celebration has made common knowledge of the fact that the nation's first commercial well drilled for oil was under the supervision of Edwin L. Drake at Titusville, Pennsylvania. Less widely realized is the fact that it was in the oil fields of Pennsylvania that experiments were first initiated which led to the widespread use of vacuum, water flooding, and air-gas drive as methods of recovering additional crude oil from apparently depleted sands. Pennsylvania led the nation in the volume of crude oil produced from 1859 to 1895, and, though the quantity of production in the state has diminished since then, Pennsylvania still produces a preferred lubricating oil used throughout the world.

STRUCTURE and STRATIGRAPHY

The oil pools in western Pennsylvania occur in the northern part of the Appalachian Basin, a broad asymmetrical structural trough or synclinorium whose long axis trends in a northeasterly and southwesterly direction, with the steep limb on the southeast side. Figure 1 is a geologic map which exhibits the large-scale structural units in Pennsylvania. The regional dip of the strata containing the oil sands is about 25 feet per mile in a south-south-west direction, with the oil sands therefore increasing in depth in that direction.

A series of rather prominent anticlinal and synclinal folds, with axes trending approximately parallel to the long axis of the basin, modifies the southeast side of the Appalachian Basin in Pennsylvania. These folds become less numerous to the northwest. The oil pools (Fig. 2) are located along the northwestern margin of this belt of folds, where the folds have become relatively broad and gentle.

The producing oil sands of Pennsylvania are not continuous bodies of sandstone, but consist of numerous lenses occuring at depths of 400 to 3,000 feet.

Most of the water flooding projects are located in the Northern District (Fig. 3) in which the Bradford District is located, while the air and gas drive projects are located in the Middle District, with two such projects in the Southwestern District.

With the exception of the Second Venango Sand of the Conewango Group (Upper Devonian in age), all of the sands under water flooding are in the Canadaway Group (also of Upper Devonian age) (Fig. 4). The sands under air or gas drive are from both of the above mentioned groups and one sand, the Berea, is in the Pocono Group (Mississippian age). The use of secondary recovery methods in Pennsylvania has made it economical to operate the oil fields long after they would otherwise have be abandoned.

HISTORY OF SECONDARY RECOVERY IN PENNSYLVANIA

Vacuum

John Franklin Carll[1], Assistant State Geologist in charge of petroleum and natural gas investigations for the Second Geological Survey of Pennsylvania, mentioned in a report published in 1890 that vacuum had been used in the Triumph Oil District of Pennsylvania as early as 1869 to increase the recovery of crude oil from the oil reservoir. (The term "vacuum" is customarily used in the oil and gas industry to denote a pressure less than atmospheric, but not implying absolute vacuum.) Later it was discovered that vacuum increased the volume of recoverable casinghead gasoline, as well as the volume of crude oil. Within ten years after drilling of the Drake Well, the application of vacuum to reservoir pressures was adapted by the Pennsylvania oil producers. This technique has been practiced continuously somewhere in these fields up to the present

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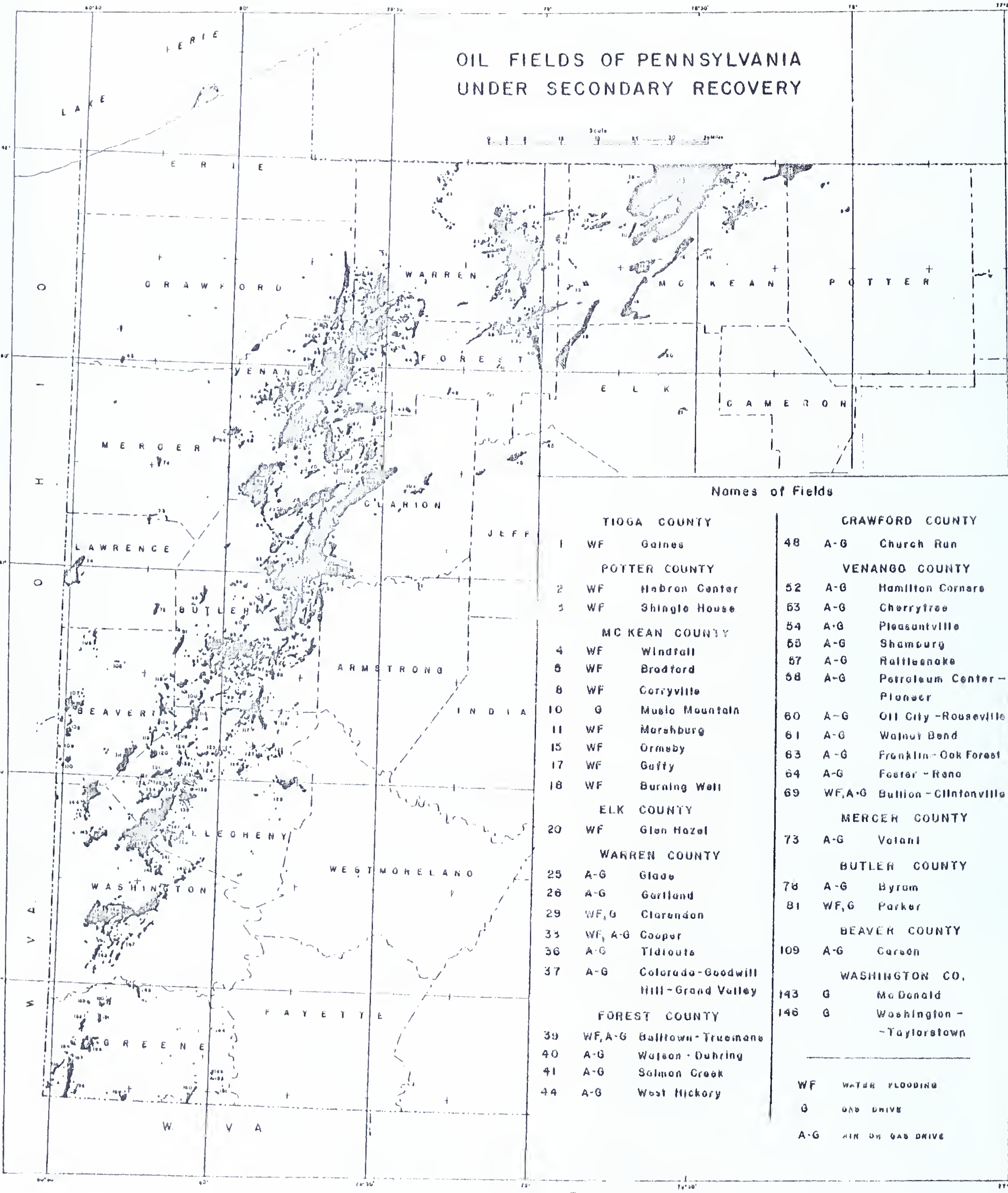

OIL FIELDS OF PENNSYLVANIA
UNDER SECONDARY RECOVERY
LAKE ERIE
ERIE
CRAWFORD
WARREN
MC KEAN
POTTER
FOREST
ELK
CAMERON
VENANGO
MERCER
CLARION
LAWRENCE
BUTLER
ARMSTRONG
INDIA
BEAVER
ALLEGHENY
WESTMORELAND
WASHINGTON
FAYETTE
GREENE
W. VA
OHIO
W. VA
Names of Fields
TIOGA COUNTY
1 WF Gaines
POTTER COUNTY
2 WF Hebron Center
3 WF Shingle House
MC KEAN COUNTY
4 WF Windfall
5 WF Bradford
8 WF Corryville
10 G Music Mountain
11 WF Marshburg
15 WF Ormsby
17 WF Guffy
18 WF Burning Well
ELK COUNTY
20 WF Glen Hazel
WARREN COUNTY
25 A-G Glade
26 A-G Gartland
29 WF, G Clarendon
33 WF, A-G Cooper
36 A-G Tidioute
37 A-G Colorado-Goodwill Hill-Grand Valley
FOREST COUNTY
39 WF, A-G Balltown-Truemans
40 A-G Watson-Duhring
41 A-G Salmon Creek
44 A-G West Hickory
CRAWFORD COUNTY
48 A-G Church Run
VENANGO COUNTY
52 A-G Hamilton Corners
53 A-G Cherrytree
54 A-G Pleasantville
55 A-G Shamburg
57 A-G Rattlesnake
58 A-G Petroleum Center-Pioneer
60 A-G Oil City-Rouseville
61 A-G Walnut Bend
63 A-G Franklin-Oak Forest
64 A-G Foster-Reno
69 WF, A-G Bullion-Clintonville
MERCER COUNTY
73 A-G Volant
BUTLER COUNTY
78 A-G Byrom
81 WF, G Parker
BEAVER COUNTY
109 A-G Carson
WASHINGTON CO.
143 G McDonald
146 G Washington-Taylorstown
WF WATER FLOODING
G GAS DRIVE
A-G AIR OR GAS DRIVE

Figure 2

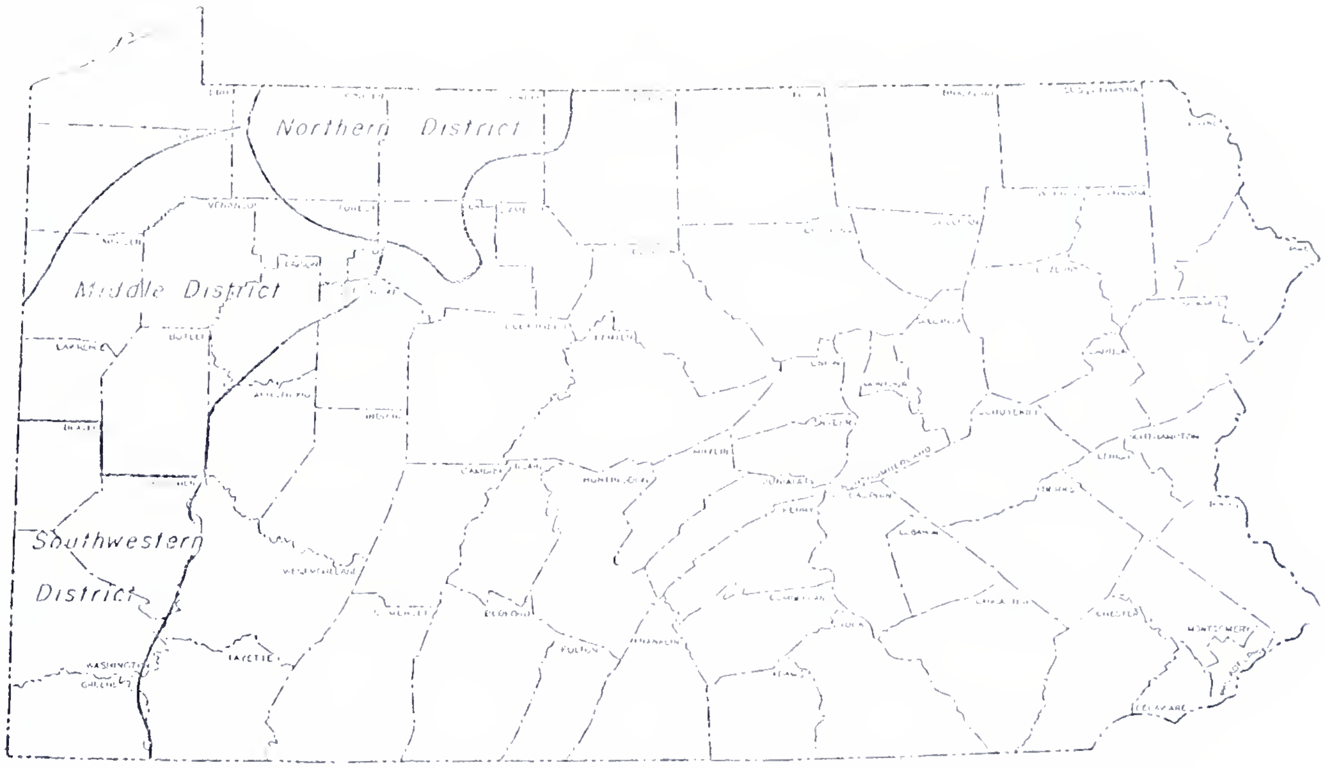


Figure 3. CRUDE OIL PRODUCING DISTRICTS IN PENNSYLVANIA

time. Oil production, as a rule, is stimulated only slightly by the application of vacuum, and for a comparatively short time. 4 to 10 gals. of gasoline are recovered per 1000 cu. ft. of gas after compression. The use of vacuum in Pennsylvania was at its height from 1918 to 1925. The total amount of additional oil recovered and the present production by this method are not known, but in both cases the amount is relatively small. About 19 percent of the present crude oil production in the state can be attributed to "natural" production, and vacuum. The resultant increase in the viscosity of the oil from the use of vacuum has probably left the remaining reservoir oil more difficult to recover.

Water Flooding

The first recorded unintentional water flood occurred about 1876-1877. An account of this flood is given in "Empire Oil" by John Herrick[2]. The author states that the flood occurred about 1876 on the Columbia Oil Company property along Oil Creek about one and a half miles south of Petroleum Center, Vanango County. Fresh water entered the Vanango Third Sand either as a result of pulling the pipe during abandoning operations, or because of deterioration of the seed bags which were used on the tubing to keep the fresh water from entering the oil horizon below. The resultant flooding of the Vanango Third Sand was first noticed on the adjoining Barcroft and Kirkwood lands where wells increased in oil production. Barcroft and Kirkwood soon determined that the increase was due to the water entering the oil producing horizon in wells on the Columbia Oil Company's property. To keep the Columbia people from finding out about the flood, Barcroft and Kirkwood sold their oil to several refineries and even hauled it out at night in barrels. When the Columbia people found out about the flooding, they re-conditioned the old wells and shut off the water, thus reducing the water drive and causing the production of the Barcroft and Kirkwood wells to decline.

In a report published in 1880 by the Second Pennsylvania Geological Survey, John F. Carll[1] first called attention to the possibilities of employing water flooding to increase the recovery of oil from the oil sands. In this report Carll made the following statement: "The flooding of an oil district is generally viewed as a great calamity, yet it may be questioned whether a larger amount of oil can not be drawn from the rocks in that way than by any other, for it is certain that all the oil cannot be drawn from the reservoir without the admission of something to take its its place.

SYSTEM	GROUP	FORMATION	SECONDARY RECOVERY METHOD IN USE
		PITTSBURGH COAL	
PENNSYLVANIAN	CONEMAUGH	MURPHY SAND	
		AMES LIMESTONE	
		SALTSBURG SAND	
		LITTLE DUNKARD SAND	
		BIG DUNKARD SAND	
	ALLEGHENY	UPPER FREEPORT COAL	
		FIRST GAS SAND	
	POTTSVILLE	FIRST SALT SAND	
		SECOND SALT SAND	
		MAXTON SAND	
MISSISSIPPIAN	GR	GREENBRIER LIMESTONE	
	POCONO	LOYALHANNA LIMESTONE	
		BIG INJUN SAND	
		SQUAW SAND	
		CORRY, BEREA, SECOND GAS SANDS	A-G*
		MURRYSVILLE SAND	
DEVONIAN	CONEWANGO	HUNDRED FOOT, FIRST, AND GANTZ SANDS	A-G
		FIFTY FOOT, WHITE, AND ROSENBERRY SANDS	
		LYTLE AND RED VALLEY SANDS	A-G
		UPPER NINEVEH SAND	
		SECOND, THIRTY FOOT, AND LOWER NINEVEH SANDS	A-G, WF†
		SNEE AND GORDON STRAY SAND	
		BOULDER, KNOX THIRD, AND SHIRA SANDS	A-G
		KNOX FOURTH, THIRD STRAY, CLARION, GRAY AND GORDON SANDS	A-G
		DYRAM, KNOX FIFTH, THIRD, AND FOURTH SANDS	A-G
		FIFTH SAND	A-G
	CONNEAUT	BAYARD SAND	
		ELIZABETH SAND	
		"PINK ROCK"	
	CANADAWAY	BRADFORD FIRST, QUEEN, AND GLADE SANDS	A-G
		WATSONVILLE SAND	
		CLARENDON, KINZUA, SUGAR RUN, AND DEWDROP SANDS	A-G, WF
		SPEECHLEY AND BALLTOWN SANDS	A-G
		CHERRY GROVE, GARLAND, AND CHIPMUNK SANDS	A-G
		BRADFORD SECOND SAND	WF
		COOPER AND HARRISBURG RUN SANDS	A-G, WF
		KLONDIKE, DEERLICK, AND SLIVERVILLE SANDS	G‡
		BRADFORD THIRD SAND	WF
		LEWIS RUN SAND	
		UPPER KANE SAND	WF
		LOWER KANE SAND	
		SARTWELL SAND	WF
		HASKILL SAND	WF

* AIR OR GAS DRIVE
† WATER FLOODING
‡ GAS DRIVE

"If one company owned all the wells drawing upon a pool, and had accurate records of the depths and characteristics of the oil producing stratum in each well, it is quite possible that some system might be devised by which water could be let down through certain shafts, and the oil forced towards certain other shafts where the pumps were kept in motion, and thus the rocks be completely voided of oil and left full of water. As it is, however, no systematized plan of action can be adopted. The careless handling of one well, by which water is let down to the oil rock, may spoil several others belonging to different parties. A clashing of interests at once arises and is likely to result in disaster to the whole district."

Either nobody noticed Carll's report or those who did were afraid to discuss it openly because of the law against letting water into the oil sands. By the early 1890s, however, there was some intentional, but secret, water flooding in the Bradford Field. Perhaps someone had been re-reading Carll's book, or perhaps operators had noted that some wells would first increase in oil production and then eventually yield water, as Carll had noted in his report.

For a number of years the "dump" flood method to let water in on the sand was used in the Bradford District. This method involved pulling the pipe out of certain wells, allowing the fresh water to enter the oil sand. Later a number of additional wells were drilled around the area of advancing water, for the old wells were often spaced too far apart for efficient flooding. Because of this additional drilling, the method became known as the "circle" flood. It was found that much better results could be obtained by tubing the intake wells, thus keeping the wall cavings away from the face of the sand.

About 1907 the effects of flooding became noticeable in the annual production of the Bradford District. Because Pennsylvania law required that abandoned wells and dry holes be plugged to prevent water from entering the oil and gas sands, the flooding was done more or less secretly.

A special act was passed in 1921 by the Pennsylvania Legislature, legalizing the flooding practice when applied to the Bradford and certain other specifically named sands. The act was amended in 1923 to include additional sands and again in 1929 to add another sand to the list. With the passage of these acts, water flooding was extended rapidly and improvements were quickly made in this secondary recovery method.

The Forest Oil Company, realizing that the old "circle" flood was a more or less haphazard operation, started in 1922 the "line" type of flood in the Bradford Field. Two rows of oil wells were staggered on both sides of an equally spaced line of water intake wells. Within two or three years, the oil wells reached their economic limit of production, at which time another row of oil wells was drilled ahead of the flood and the former oil wells were then converted to water intake wells.

In 1928, the "five-spot", a more intensive method, was introduced. A whole tract was laid out in a pattern of squares with water intake wells at the corners of the squares and the producing wells at their centers. Frank Haskell[3] of the Associated Producers Company is credited with the idea of the "five-spot" pattern. In 1924 this company attempted an operation with this pattern, but due to the extremely wide spacing of water intake wells, 500 feet apart, and the low permeability of the sand, very little increase in oil production was obtained.

It was not until 1927-1928 that the possibilities of intensive and systematic water flooding were clearly demonstrated. A "five-spot" development was undertaken by Arthur E. Yahn[3] of Olean on the Kuno-Kuhn property in the northeastern part of the Bradford Field. Good results were obtained in this project and the use of the "five-spot" method spread rapidly.

"Pressure flooding" was introduced at about this same time. This development involved the application of additional hydraulic pressure to that of the hydrostatic head of the column of water in the intake well. Although this had already been tried in 1925 and 1926 in the Bradford Field with promising results, it did not attract much attention until 1928 when John Messer[3] of Bolivar, New York, tried it on a Richburg Pool property in a "five-spot" flood. So satisfactory were the results that this method of water flooding is the one used in most such secondary recovery operations today.

In general, 10 to 25 bbls. of "flood" water are required to produce a barrel of oil. The flood water which is introduced under pressure at the top of the intake well comes primarily from shallow, fresh water wells, but also from surface water and springs. The water is sometimes processed through an open system which involves considerable treatment and filtration before injection. During the last few years, however, more operators have changed over to the closed system in which the floodwater is obtained from shallow fresh water wells and injected with a minimum of treatment or filtration, without being exposed to the air. The pressure applied in the intake wells is as high as 1800 to 2000 psi at the sand face. The distance between

intake and producing wells usually varies from 200 to 300 ft. Oil wells are generally pumped, but some are produced by the method of back-pressuring and flowing the oil. Some holdings in the Bradford Field have produced over 10,000 bbls. per acre as a result of flooding operations.

Some operators, in contrast to the usual closer spacing, have gone to 500 foot well spacing. Closer spacing will result in recovering the oil more quickly, but also in increasing the overall cost of recovery. Patterns other than the five-spot are used to fill in areas where property lines will not permit the use of the five-spot.

Most of the successful water floods in Pennsylvania are located in the Northern District (Fig. 2). In the Middle District there is a successful flood in the Second Sand reservoir of the Bullion-Clintonville Field. Except for this flood and a recent water flood experiment in the Parker Area, Butler County, which shows signs of success, floods have not been successful in the Middle District. The Bradford Field, located in the Northern District, contributes the major part of the oil in Pennsylvania obtained by water flooding. Other successful floods in the Northern District are being conducted on a fairly extensive scale in the Clarendon, Guffy, Burning Well, and Shingle House Pools and, on a smaller scale, in the Hebron Center, Corrysville, Glenhazel, Marshburg, Ormsby, Kings Run, and Windfall pools. Water flooding in the Gaines Pool and Cooper Field has not been very successful. The Clarendon Pool obtains its oil from the Clarendon Sand (Fig. 4) whereas oil in the other pools is obtained from the Bradford Third Sand (or a sand at approximately the same stratigraphic horizon). The Bradford District consists of about 100,000 acres in the Northern District and includes the production from the Bradford Field (14 percent lies in New York), Guffy, and Burning Well pools. Over 90 percent of the production from the Bradford District comes from the Bradford Field.

Air and Gas Drive

The first recorded attempt to obtain additional recovery of oil by the injection of gas was made in 1890-91 by James D. Dinsmoor[4] on the Benton Farm, Venango County, Pennsylvania. Dinsmoor intentionally diverted high pressure gas from a deeper formation into the Third Venango Sand of the same well by shutting in the well. The oil production of wells adjacent to the input well was more than doubled as a result, and in a short time the production from the entire property was likewise increased.

Mark B. Mitchell[5] of Franklin in the early 1900s made the first recorded attempts to repressure oil sands in Pennsylvania. A patent on the method was applied for in 1904 and granted in 1906. The Brundred Oil Company of Oil City, Pa., obtained the rights in 1914 for the use of the process. The patents were later declared invalid.

The Hamilton Corners Pool[6] in Cherry Tree and Oakland townships, Venango County, Pennsylvania, was first subjected to air and gas injection in 1916. This project represents probably the first successful attempt[4] in the history of the oil industry in the United States to combine the holding of several owners, by purchase and by agreement, so that an entire pool could be operated as a unit under one management.

Following this first successful repressuring project by Mitchell, the use of air or gas as a driving medium to increase oil production continued to increase and by the middle 1920s was widespread in the Pennsylvania oil fields. Production resulting from air or gas injection reached its peak in 1929. The method is used extensively today, particularly in the Middle District, and thirteen percent of Pennsylvania's 1958 production can be attributed to air or gas drive.

In the early days of air or gas drive, the development of a project was haphazard. Sometimes a gas well was shut in and the gas allowed to enter any porous bed below the casing point. But when more emphasis was given to technique and efficiency, tubing and packers were installed in input wells. As symmetrical a well spacing pattern as was possible with the old wells was sought and pumps were used to force the gas into a particular bed. A pattern known as the "reverse seven-spot" (in which each producing well was affected by three inputs) was developed. This pattern became standard for intensive development, the spacing being 150 to 250 feet between inputs and producers, which is a much closer spacing than was used earlier. In general, 1000 cu. ft. of air or gas per vertical foot of sand is injected daily into each input well under pressures ranging from 50 to 400 psi. During the life of a project, from 6 to 22 Mcf of air or gas is injected per barrel of oil produced. From 10 to more than 100 bbls. of oil per acre-foot can be expected to be produced by air or gas drive in the average secondary-recovery project in Pennsylvania. Dickey and Bossler[7] in a paper "Oil Recovery by Air and Gas Drive in Pennsylvania", indicated that after recovery by mechanical methods, excluding heat and solvents, 150 barrels or more of oil per acre-foot are left in the reservoir.

Air or gas drive is used extensively in the following fields (Fig. 2): Music Mountain, Cooper, Tidioute, Colorado-Goodwill Hill-Grand Valley, Balltown-Truemans, Watson-Duhring, Church Run, Pleasantville, Shamburg, Petroleum Center-Pioneer, Oil City-Rouseville, Foster-Reno, Cranberry-Rockland, Bullion-Clintonville, Volant, and Carson, and less extensively in the Gartland, Kinzua, Walnut Bend, Clarion-Lucinda, McDonald and Washington-Taylorstown fields.

The sands (Fig. 4) under air or gas drive are the Berea, First, Lytle, Red Valley, Second, Knox Third, Third Stray, Gray, Gordon, Third, Fourth, Fifth, Balltown, Cooper and Sliverville.

At present there are approximately 2000 air or gas input wells affecting 7000 producing oil wells in Pennsylvania's air or gas drive projects.

Technical Advances

John F. Carll's[1] report of 1880, mentioned previously, probably contains the earliest estimate of the porosity in an oil reservoir. In this report Carll makes the following statement: "We have said above that experiments made in a crude way indicate that an oil sand may contain as much as one-tenth of its bulk in oil. There can be little doubt, however, that a good rock in its normal condition and under pressure might hold an equivalent of one-eighth."

In the same publication he considers the variations in a reservoir's capacity to deliver oil into the well bore, in which formation permeability is a factor, by pointing out that "no account is here made of the friction encountered by the oil in passing through the thousands of pores in the sandstone, nor of the compensating force of gas impelling the oil under a tremendous pressure through them.

"This imperfect calculation is not intended to show just how much oil a porous rock could deliver, but simply to exhibit the possibilities of a flow through and from it, equal even to the full capacity of the well-bore. When there is from five to ten feet of this kind of rock to drill through, it can readily be seen that a flow of three or four thousand barrels per day might easily be maintained through the operation of these numerous oil leads, making ample allowance for friction and all other contingencies, without requiring the aid of crevices to convey the oil into the well."

With respect to the occurrence of oil and gas, Carll states: "Oil and gas, in their normal conditions, appear to lie in the sandrock not as distinct bodies occupying separate portions of the rock, but as one substance, the gas being as thoroughly incorporated with the oil, as gas is with water in a bottle of soda water." He also remarks: "As a general rule, the first oil wells in a prolific district produce but little salt water with the oil, unless they are located in shallow territory where the oil rock lies in such a position as to be somewhat affected by communication with the surface."

John F. Carll suggested that water flooding should result in recovery of additional oil and advanced some theories on porosity, permeability, and the presence of saltwater in the producing sand along with the oil. However, it was not until more than thirty years later that his theories were seriously considered and found to be essentially correct.

In October, 1917, the Bureau of Mines published its Bulletin No. 148 on "Methods for Increasing the Recovery from Oil Sands", by J.O. Lewis[8]. Despite the meager data available to Lewis, his report is a remarkably accurate and precise study of the factors which control the performance of oil reservoirs. As stated by Paul D. Torrey[9] "Lewis correctly analyzed the effect of dissolved gas, of viscosity of the crude oil, and of capillary phenomena on oil recovery. He recognized, without the benefit of core analysis, the variable lithology of most oil-bearing rocks, and he appraised accurately the effect of heterogeneous permeability on the movement of injected fluids and on the production of oil, even though the term 'permeability' hadn't been applied at that time to one of the physical characteristics of porous rocks."

The report of investigation by an AIME committee on the "Determination of Pore Space of Oil and Gas Sands" was published in 1920[10]. This was followed in 1921 by another AIME report on the same subject by A.F. Melcher[11]. The same author, in a paper published by the AAPG[12] described in 1924 a technique for the determination of porosity, listed the porosity of numerous oil reservoirs, and discussed the significance of reservoir porosity to the production of oil.

Melcher[13], in 1925, is believed to have made the first determination of the porosity of a complete cored section of reservoir sand when he made his calculations on a core from the Bradford Field.

Charles R. Fettke[14], in a paper on "Core Studies of the Second Sand of the Venango Group, from Oil City, Pa.", described (in 1926) a determination of oil and water saturations by distillation. The graphic profile of the porosity of an oil sand which appeared in this paper is believed to be the first ever published.

A new method for determination of porosity was described by W. L. Russell[15] in 1926. Paul D. Torrey used this method in the first commercial core laboratory, which was established in Bradford, Pennsylvania, in 1928. Early proof of the existence of water in oil-bearing rocks was demonstrated by Torrey in 1928[9] and Fettke, in 1929[16], in core analyses of the Bradford Sand.

A. C. Simmons[9] designed an adaptation of the Washburn-Bunting apparatus for the determination of the porosity of reservoir rocks, first used in 1929. It is the most commonly used equipment for the determination of the porosity of reservoir rocks.

Melcher[17], in 1922, gave the first detailed discussion of "permeability" as it refers to the fluid-conveying capacity of oil reservoir rocks. Clark F. Barb[18] and Fettke[19] separately reached the same conclusion, almost simultaneously, that the porosity of oil reservoir rocks was no criterion of their permeability.

In 1933[20] a paper by Wycoff, Botset, Muskat, and Reed defined the "Darcy" as the unit of measurement of permeability. During the same year, Fancher, Lewis, and Barnes[21] contributed the most extensive study of permeability made up to that time.

Since the early 1930s, experimental work has continued in petroleum technology, many important phases of which had their beginnings in Pennsylvania.

During the summer of 1924 the diamond core was first used to investigate oil-bearing sands when the Northwestern Pennsylvania Oil Producers Association cored a well one-half mile west of Custer City[3]. This was the core used by Melcher for his porosity determinations mentioned above. Cable tool coring using the Baker core barrel was intorduced by Sloan and Zook Company in 1928 in the Bradford Field[3]. The chip core and a technique to run tests on such a core were developed by Ryder-Scott of Bradford in 1937.

Pennsylvania State University[22] initiated a program in 1929 for industrial research, in which there was equal emphasis on production and the refining of crude oil. Four years later (in 1933) the Bradford District Pennsylvania Oil Producers Association [23] added its support to the program. In 1943 the research program was adopted by the Pennsylvania Grade Crude Oil Association. The Association established at the same time a research project of its own in secondary recovery. In 1944 the Association, joined by various industries in the Pennsylvania Grade Area, raised a $300, 000 fund to support three years of research for better oil recovery[22]. The institutions at which this research program was carried out were Pennsylvania Grade Crude Oil Association Laboratory, Pennsylvania State University, Battelle Memorial Institute, St. Bonaventure College, and the U. S. Bureau of Mines at Franklin, Pennsylvania.

In addition to the research mentioned above, several oil companies operating in Pennsylvania established their own research laboratories. The Penn Grade Laboratory was discontinued in 1955, but secondary recovery reserach is continuing today in oil company laboratories and at the Pennsylvania State University.

Following is a brief summary of some of the noteworthy achievements made by the Pennsylvania Grade Crude Oil Association Laboratory.

Experiments were run on slow and high rates of water injection. The results showed that the higher rates of injection resulted in a recovery of more oil. Pre-gas injection in a water flood resulted in a quicker response to flood water. The work done with Dresinol proved it to be a good plugging agent. The use of wetting agents was found to increase oil recovery, but the cost of such practice was found to be prohibitive. A number of good corrosion inhibitors were developed and made available. The role of carbon dioxide in a sand was investigated. In addition, the Penn Grade Laboratory solved many individual problems which were submitted by producers.

Robert F. Mackie[22] started a laboratory in 1934, specifically to help the oil producers with their water problems. This early work was performed in the Bradford Field. Other laboratories were established to work on water problems. Ryder-Scott of Bradford did considerable early experimental work in well-spacing and selective shooting. S. T. Yuster and J. C. Calhoun, Jr., of Penn State University, published an early paper[24] describing laboratory and field work on a wide variety of plugging materials. This paper was quickly followed by other papers on the same subject. Another significant contribution to oil field technology was the early work on the shield electrode, a logging technique, by Howell at Pennsylvania State University.

The Bradford region has gained recognition today as the greatest secondary recovery laboratory in the world. Many new improvements in oil recovery techniques came out of research in this region. Water flooding progressed from the inefficient dump flood to the line flood to the more efficient five-spot flood. Input wells were tubed. Coring was initiated. Methods for determining porosity and permeabilities were invented. Pressure flooding was introduced. Improvement was made in drilling and cleaning out. Selective shooting was introduced. Interpretation of electric and other logs improved. Drill cutting descriptions became more detailed. Wells were better spaced for maximum oil recovery. Pumping schedules were improved. Knowledge of water treatment increased. The use of electric jacks was introduced, and many other improvements were developed.

The following can be said of the newer techniques used today in water flooding procedure in Pennsylvania. Selective plugging with a soft wax emulsion, with a hard oil-insoluble resin emulsion, and with various plugging agents in an oil mixture, all have been used successfully in some areas. Probably the plugging agent most widely used today is a resin dispersion known commercially as Dresinol which is used to plug highly permeable sands. The flood water used today generally comes from a closed system which excludes oxygen. It is a filtered, non-acidic water to which a stabilizing agent has been added. Treatment of the water filters out the solids, cuts down corrosion, and keeps the minerals in solution. A form of acidizing is used which is unique to Pennsylvania in that it restores permeability to the sand on which salts and minerals have been deposited in the water input well. The treatment consists of introducing into the shot hole 150 gals. of 20 degree Baume hydrochloric acid containing an inhibitor. Wider spacing is being tried in five-spot layouts with distances as high as 550 feet between water-input wells. Quicker recovery can be had by closer spacing, but development costs are higher here than in the wider spacing. Since 1865, when Col. E. A. L. Roberts exploded his first torpedo in the Ladies well near Titusville [25], the producing sands in Pennsylvania's oil fields have been shot as a part of routine completion procedure. With the development of selective shooting, increased recovery in secondary projects has been obtained. The loose part of the sand is given a "light shot" and the tight section a heavier shot. Hydraulic fracturing has recently been used in water flood projects in northern Pennsylvania. After casing through the sand, perforating, and acidizing the input or producer, the oil zone is fractured with [illegible]0 gals. of oil (or water) and 400 pounds of sand per foot of prospective producing interval. The injectivity of the input well and the productivity of the producing well are increased, apparently improving the rate of oil recovery. Pre-injection of 400 to 600 Mcf of gas into water input wells of a water flood project, as was mentioned earlier, has been found to cause the flood to respond more quickly. With the installation of automatic electric pumping jacks, which results in a regular pumping schedule and therefore a regular build-up and release of pressure on the sand face due to the rise and fall of the fluid in the shot hole, the production has increased on a number of properties.

A fireflood experiment is being conducted in the Allegany Field in New York State. During the first field test of this experiment, ignition could not be achieved. It is too early to evaluate this method of recovery as applied to the oil fields of the northern part of the Appalachian Basin. Recently, in two gas-drive projects in southwestern Pennsylvania, slugs of casinghead gasoline were dumped into input wells periodically. No attempt has been made, as yet, to evaluate the success of this experiment.

Many of the above improvements and new techniques can be applied equally well to air or gas drive projects as to water flood projects.

Present Status of Secondary Recovery

Crude oil production in Pennsylvania reached its peak (Fig. 6) in 1891 when 31,424,000 barrels were produced by primary methods. The McDonald Field flush production was largely the cause of this production peak. After a period of declining production, a secondary peak of 19,990,000 barrels was attained in 1937, largely by secondary methods. Since this secondary peak, production has slowly declined to a low of 6,677,000 barrels in 1958. Dating from the discovery of the Drake Well in 1859, Pennsylvania's oil fields have produced over 1,219,070,000 barrels of crude oil (as of January 1, 1959). This figure includes an estimated 10,000,000 barrels which ran to waste for want of a market prior to 1863.

The total recovery in Pennsylvania by secondary methods was 347,158,000 barrels by 1959, 327,662,000 barrels of which were produced by water flooding and 19,496,000 barrels by air or gas drive. The total natural production at the close of the same period was 871,912,000 barrels.

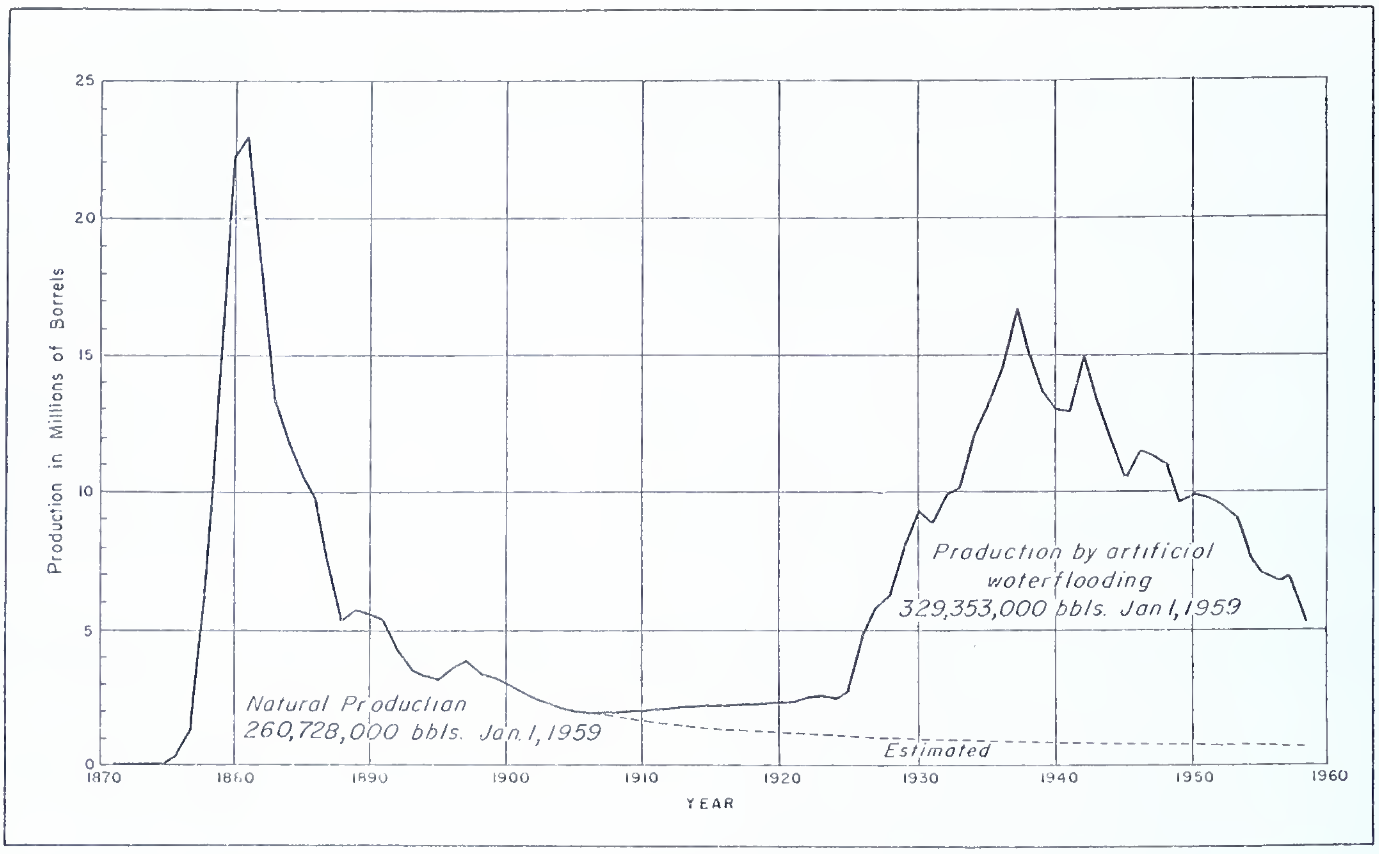
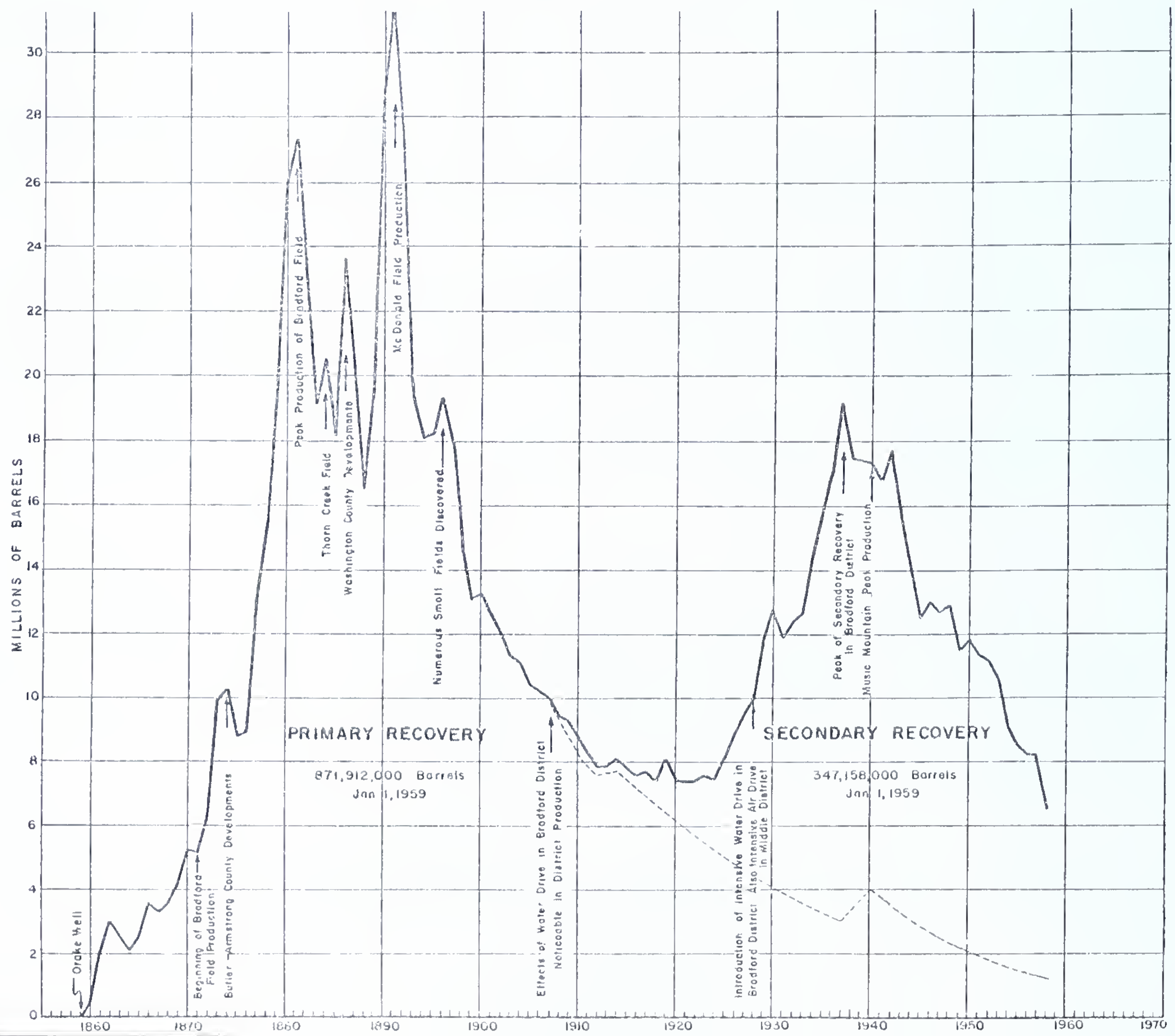


Fig. 5. Crude oil production curve of the Bradford district, Pa. & N.Y.
Music Mt. field excluded



The Bradford District, consisting of about 100,000 acres, is located in the northern crude oil producing district of Pennsylvania, and includes the production from the Bradford Field, 14 percent of which lies in New York, and the Gufley and Burning Well Pools. By January 1, 1959, the Bradford District had produced about 590,081,000 barrels, of which 260,728,000 barrels (Fig. 5) can be attributed to natural production and 329,353,000 barrels to flood production. In Figure 5, the primary recovery curve from 1907 to 1959 is estimated.

The Northern District is responsible for over 74 percent of the present Pennsylvania oil production, while the Middle District is producing 20 percent and the Southwestern District 6 percent. Most of the oil fields in the Northern District are operating under water flood. In the Middle District, air or gas drive is used almost entirely. The only field in the Middle District under water flood is the Bullion-Clintonville in southern Venango County. In the Southwestern District, about 70 percent of the Washington-Taylorstown Field and 20 percent of the McDonald Field are under gas drive. The rest of the fields in the Southwestern District have never operated under secondary recovery methods except vacuum. Some fields in each district are presently operating under vacuum and have been operated this way for a number of years.

The Bradford Pool in Pennsylvania covers 72,200 acres. Approximately 4,000 acres in the pool proper and 9000 marginal acres are yet to be developed under secondary recovery methods. 5,000 acres have been abandoned, leaving 54,200 acres at present under flood. There are approximately 500 water flood projects in operation in the pool, consisting of about 22,000 water input wells and 20,000 producing oil wells. The peak year for primary production in the Bradford District was 1881 when 22,945,000 barrels of crude oil were produced. The peak year of production by water flooding was 1937 when production for the district amounted to 16,690,688 barrels.

About 2,000 input wells and 7,000 oil wells are operating in 135 air or gas injection projects today.

Sixty-eight percent of the State's 1958 production can be attributed to water flooding, 13 percent to air or gas injection, and 19 percent to natural production and vacuum. The petroleum industry in Pennsylvania is operating 90,054 wells - 24,000 are input wells in secondary recovery projects and 66,054 are producing oil wells. About 39,000 of the above are producing either naturally or under vacuum.

Future Possibilities

Pennsylvania's crude oil production by secondary methods has been declining since 1937. This trend has been accelerated during the past few years by unfavorable market conditions. Operators have not been able to drill the wells needed or expand their operations to new areas. The proven reserve figure of 120,018,000 barrels (as of Jan. 1, 1959), could be increased appreciably with a slight improvement in the price structure and additional technological advances in recovery methods.

The total number of wells drilled in the Bradford District during 1958 was 321. This is the smallest number of completions in the history of the District except for 1955 when only 317 wells were drilled. Because production in this district depends solely on the rate at which the area's secondary recovery operations are expanded, it is evident that production is at a new low. In the years 1943 to 1948, the new wells drilled in the Bradford District averaged over 2000 per year and production remained fairly constant. With a decrease in drilling to a little over 1000 wells yearly between 1950 and 1953, a corresponding decrease occurred in production. With a low in 1955 of 317 wells, production dropped to a still lower level. In 1957 production fell off sharply. If the 13,000 undeveloped acres in the Bradford pool were developed in the near future, production would increase. If insitu combustion, solvent recovery or some other method of tertiary production proves itself for this district, considerable reserves would be added.

The rest of the Northern District and the northern part of the Middle District can be classified in the same category of development as the Bradford District. Some fields are operating under water flooding but most of the area is under air or gas drive. Development has almost ceased, not much area is left to be developed, and production is rapidly declining.

From northern Butler and Clarion Counties to the southern state line there are over 250,000 productive acres, of which only 20 percent have been subjected to air or gas injection. Air or gas repressuring has been generally successful where it has been tried in this area. Depths to producing horizons range from 700 to 3000 feet. By the time secondary recovery methods were established, many wells had been abandoned. While rehabilitation of a number of the leases could be accomplished with relatively small ex-

penditure of labor and materials, most of the abandoned leases, or areas in which an occasional well is still operating, would require considerable re-drilling before secondary recovery methods could be initiated. The development cost of such a program would be high and a considerable rise in the price of oil would be required before secondary recovery would be economical.

Wildcatting has been active in Pennsylvania since 1859. It is, perhaps, questionable whether new discoveries will provide as much oil in the future as would the extension of secondary methods, but there can be not doubt that substantial reserves would be added by wildcatting.

Drilling costs are prohibitive in southwestern Pennsylvania so long as the price of crude oil remains at its present level. Spacings are relatively wide in this district, ranging up to 20 acres per well. There is a much larger quantity of recoverable oil per acre-foot of sand in the Southwestern District than in the Middle District. The reason for the large amount of remaining oil in the Southwestern District is the absence both of intensive initial development and efficient secondary recovery operations.

Although the application of gas drive in the Southwestern District has been ineffective when compared with the Middle District, recoveries of more than 1000 barrels per acre have resulted. Figure 7 shows the production history from 1903 to 1958 of the Wallace Heirs Lease[26] in the McDonald Field in southwestern Pennsylvania. The lease is typical of the history of production in the area. Peak primary production of this property occurred in 1895 when 56, 363 barrels were produced. The production declined until only 1745 barrels were produced from the 13 wells in 1931. Gas injection was commenced in 1932. After secondary recovery had been in operation for four years, production peaked at 13, 279 barrels and gradually declined to less than 6000 barrels in 1951 when the property changed hands. Since then the production has increased as a result of cleaning out one well and introducing a more efficient operating technique. It was estimated in 1948 that the economic limit of production would be reached in 1968 by which time an additional 184, 489 barrels would have been produced by secondary methods. But because the production of this property has been increasing during the last 7 years, instead of following the decline curve as projected in 1948, the economic limit should extend beyond 1968. This property received a more effective gas drive than did the other leases under secondary recovery in this field.

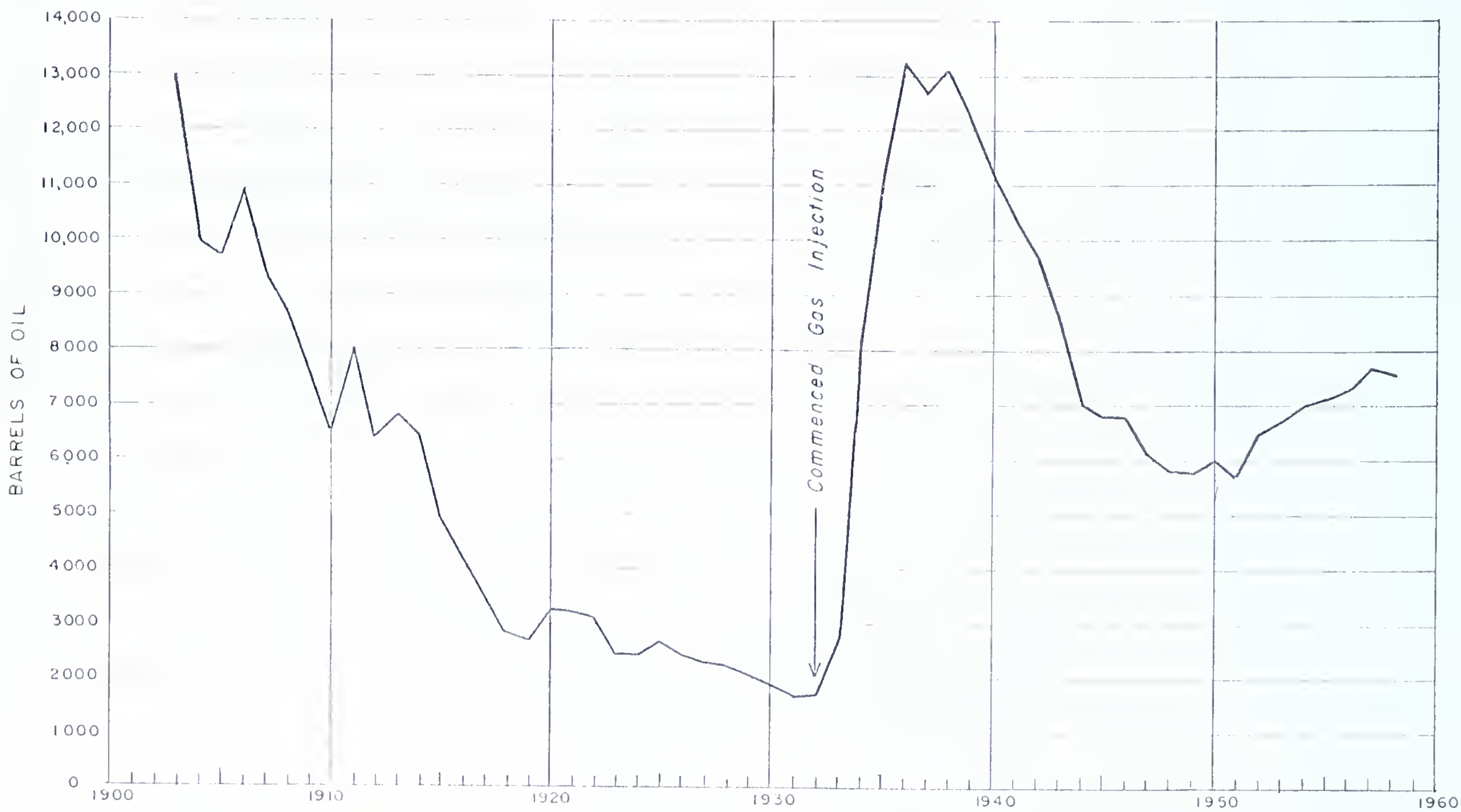


Figure 7 PRODUCTION HISTORY OF WALLACE HEIRS LEASE — MCDONALD FIELD
From 1903 to 1958

The history of production in the 25 percent of the McDonald Field in which secondary recovery methods are operating shows recoveries comparable to the Wallace Heirs property. 10,000 additional acres are yet to be converted to gas injection. Recovery statistics in the Washington-Taylorstown Field are about the same or even better than in the McDonald Field. After 15 years of operation under gas drive, some properties in this field are still operating at about peak production. Thirty percent of this field has yet to come under gas injection. There are other pools and fields in southwestern Pennsylvania which should respond as well to secondary recovery.

In summation, a price level, sufficient to substantially encourage secondary recovery, would undoubtedly result in a sizeable increase in the producing capacity of the Pennsylvania oil fields. A higher price level would encourage the operators in the Bradford District to flood the few acres remaining in the Bradford Pool proper and in the marginal areas, and to extend their operations to surrounding fields. The remaining acreage in the Middle District might be developed under air or gas drive, and under water flooding as well, if fields are found which are amenable to such a method. The 20 mile long Foxburg-Clarion Field in this district should certainly receive close scrutiny. Only experimental secondary recovery projects have been tried in this large field. The McDonald and Washington-Taylorstown fields could be completely developed under gas drive, and experimental projects might be tried in surrounding fields. With a price increase, some of the newer tertiary methods might be economical. A considerable amount of the three billion barrels of crude remaining in the Pennsylvania oil fields as unrecoverable oil might thereby be converted to proven reserves within a very short period.

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